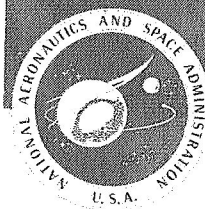


# PROBLEMS AND PROGRAMS ON THE USE OF SUBMILLIMETER WAVES IN SPACE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

PROBLEMS  
AND PROGRAMS  
ON THE USE OF  
SUBMILLIMETER  
WAVES IN SPACE

By Max R. Nagel

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*Scientific and Technical Information Division*  
OFFICE OF TECHNOLOGY UTILIZATION  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
1968  
*Washington, D.C.*



# PROBLEMS AND PROGRAMS ON THE USE OF SUBMILLIMETER WAVES IN SPACE

By Max R. Nagel  
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## SUMMARY

This report describes the development and the present status of the technology associated with the use of submillimeter waves in field and space applications and, for this purpose, offers a compilation of tables, graphs, and other data on the performance of modern submillimeter components, along with a list of the most recent literature on the subject.

The report also discusses some of the more significant achievements and the potential of submillimeter waves in the atmospheric and astronomical disciplines and in spaceflight-related operations.

A review of related programs currently sponsored by the National Aeronautics and Space Administration is given and high-priority research needs that may lead to a more effective utilization of submillimeter radiation in space are pointed out.

Two appendices are provided to fill in further details on related submillimeter problems. The approximate closing date for all data given is March, 1968.

This report is intended to serve as a data source and guide to references relating to the present status of submillimeter wave research and technology and, as such, is not meant to be a scientific treatise.

It is being made available to the scientific and technical community to stimulate interest in a re-emerging and potentially powerful scientific technique.

## INTRODUCTION

This report is intended to provide a basis and background for discussion regarding the need for submillimeter wave experimentation in the areas of the space sciences and spaceflight operations.

For this purpose, the submillimeter region -- sometimes referred to as the "far infrared" or "extreme infrared" region -- of the electromagnetic spectrum will be understood to cover,

roughly, the wavelength range between 0.1 and 1 mm, corresponding to frequencies of 3000 to 300 GHz, respectively, thus bounding with the infrared region on one side and the microwave region on the other.

An almost sudden surge of interest in the use of submillimeter waves resulted when the space program opened access to an environment transparent to submillimeter wave radiation, and, by fortunate coincidence, at the same time, several new supporting technologies emerged. Together, these developments made available a new set of technological alternatives and potentialities that neither the classical optical nor the microwave regions by themselves are able to offer.

Compared with the microwave equipments, "antennas" associated with the submillimeter region can be simple and compact. They do not require the high surface precision needed in conventional optical telescopes to achieve diffraction-limited performance; and their manufacture is easier so that larger apertures can be fabricated at correspondingly lower cost. In many applications, the combination of high-energy density with an intermediate spread of the collimated beam -- the beams spread is larger than for visible or infrared radiation, smaller than that for microwaves -- can be an important asset. Also, the specific scattering properties of the submillimeter waves may be important when dust clouds or haze penetration have to be considered.

Because of such advantageous properties, the number of new work areas and applications of submillimeter waves increases steadily. Already they have triggered the development of the entirely new discipline of Submillimeter Astronomy which is constantly expanding its scope and technological basis, and has started to produce tangible results; and applications in other fields are also contemplated.

It seems appropriate, therefore, to review the development and the present state of the art in submillimeter technology and the potential use of submillimeter waves in space. This report first discusses such uses as reflected in recent publications and proposals from the scientific community at large, and then describes the relevant programs currently sustained within NASA and, in particular, at the NASA Electronics Research Center.

## THE NEED FOR SUBMILLIMETER WAVE RESEARCH

Encouraged by the results of preparatory experiments, which will be discussed later in this report, the technical and scientific communities have become aware of the opportunities and potential of the "forgotten" submillimeter band and are now coming

forward with rapidly increasing numbers of proposals and speculations about its use in their respective fields.

It is quite apparent from analyses and planning reports that the solar physicists and astronomers will benefit most and almost immediately from the emerging new technology. This is not only because the space program prepared for them the road to a vast number of uninvestigated and still unknown research objects, but also because the imperfect submillimeter technology already available lends itself to applications within the entire spectrum of astronomical research, ranging from cosmology and the planetary sciences to solar physics.

It seems significant indeed that the new importance of submillimeter techniques for astronomy has been recognized in reports and recommendations of highest level advisory bodies, such as the President's Science Advisory Council (ref. 1)\*, the Space Science Board of the National Academy of Sciences/National Research Council (ref. 2), and a number of similarly eminent committees.

Since no submillimeter detector has yet been flown in space, it is impossible at this point to assess the impact of the new capabilities on the development of astronomical knowledge beyond the general statement that it will certainly be spectacular. Because of the comparative simplicity of the instrumentation associated with "observation-" or "detection-" type experiments, one can expect that the first truly spaceborne missions will restrict themselves to mapping and location activities and to the determination of relative energy distributions in the observed objects. It seems safe to assume that even through such comparatively unsophisticated experimentation, many diffuse objects and galaxies -- later even stars in either their ascent or decaying phases -- will be discovered by their low-temperature thermal emissions. It will also become possible to determine more accurately the position or size, and possibly the physical structure, of other objects that already have been detected by their radio frequency radiation.

Perhaps more valuable, but also more exacting, will be the radiometric, "measurement-" type programs from which quantitative radiation data can be obtained.

In cosmology, the determination of the absolute value of interstellar background temperatures through submillimeter techniques might yield more detailed insight into the thermal transfer processes involved in the origin of the Universe. One of the recommendations of the Space Science Board (ref. 2, p. 335),

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\*See excerpts on following page.

## SUBMILLIMETER RESEARCH NEEDS

### Recommendations of the President's Science Advisory Committee\*

Page 30

For scientific as well as technical reasons, we urge an immediate start on simpler instruments which can more dramatically exploit the new access to unknown regions of the spectrum—such as X-ray and gamma-ray telescopes, and relatively inexpensive submillimeter instruments.

Page 31

*Recommendations.—a. We recommend that the government adopt as a primary goal in the application of space technology for scientific purposes a program leading to the establishment in earth orbit of a number of astronomical facilities, which by the end of the decade of the 1970's will constitute an orbiting astronomical observatory capable of—*

*(1) exploring the full range of the spectrum not accessible from the ground with all the attendant advantages of instruments in orbit such as diffraction-limited resolution and coherent detection over large base lines,*

Page 31

*c. We recommend for the middle 1970's a second generation of X-ray, gamma ray, submillimeter, and radio wave-length instruments, utilizing the experience gained from the 1st generation instruments.*

Page 58/59

*d. Infrared astronomy.—*The broad range from 1 micron to 1 millimeter has been explored in a severely limited way from the ground and, with partial elimination of atmospheric interference, from balloons. Important advantages can be gained with higher altitude platforms. Present efforts are confined to rockets and represent only first attempts at utilizing cryogenic systems in connection with cooled optics and sensors. Liquid helium temperatures are essential. Three to four years of experimentation scaled to Aerobee rocket capabilities is needed to solve instrumentation problems. Scaled-up versions may then follow (up to 30-inch telescopes) to be flown on larger rockets. It is not overly optimistic to expect many surprising discoveries in this broad spectral range (exploratory phase, \$10M).

\*Clippings from the President's Science Advisory Committee, The Space Program in the Post-Apollo Period, February 1967 (ref. 1).

for example, is based on the expectation that the spectrometric analysis of the general interstellar background by means of spaceborne instrumentation will reveal important details about the age and early evolutionary history of galaxies, and that it will also assist in judging the relative merits and validity of various proposed models of the Universe. Open, closed, and flat cosmological models are now being used. Cosmologists hope also that submillimeter techniques, notably when using modern heterodyne detection methods, will make it possible to determine the chemical composition and density structure of cosmic clouds and stellar matter (ref. 3).

Another cosmological problem to which submillimeter techniques can be profitably employed is that of the radiation-generating processes in quasars. For instance, new theories are constantly advanced to explain phenomena such as the rapid changes in radiation output levels of quasars which may permit conclusions as to their size, distance, and nature (ref. 4). Synchrotron effects are probably involved, but it is suspected that other, so far undetermined, physical mechanisms are also participating in the radiation-generating processes. Absolute measurements and prolonged monitoring of radiation fluxes through the entire spectrum are necessary to clarify these questions, but only scant, if any, data are as yet available on the submillimeter and far infrared radiation emitted by the quasars detected so far (ref. 5).

NASA/ERC astronomers hope to contribute to the solution of some of the above problems through a program in which they propose to study the radiation from the Crab Nebula and possibly also the galactic center and quasistellar sources, such as 3C273, thus supplementing earlier, ground-based work on these objects (refs. 6-8).

As an illustration of the need of cosmological submillimeter research, Figure 1 shows how the submillimeter technological "gap" affects the knowledge on the radiation fluxes emitted by the Crab Nebula, the center of our galaxy, and the quasistellar source 3C273. One sees that virtually no information on the spectrum of these objects is available through two or three orders of magnitude of wavelengths which, in all cases, include the entire submillimeter region. The Crab Nebula is of particular interest because of the -- according to Bastin (ref. 9) -- "curious" upward trend of its radiation flux at higher radio frequencies (refs. 10, 11) which needs explanation. Obviously, the galactic center and 3C273 also have so far undetermined maxima somewhere in the submillimeter region. Astronomers are particularly anxious to locate these maxima as the flux gradient can provide important clues regarding the structure and energy-conversion processes in compact and intense X-ray and radio sources (ref. 12).



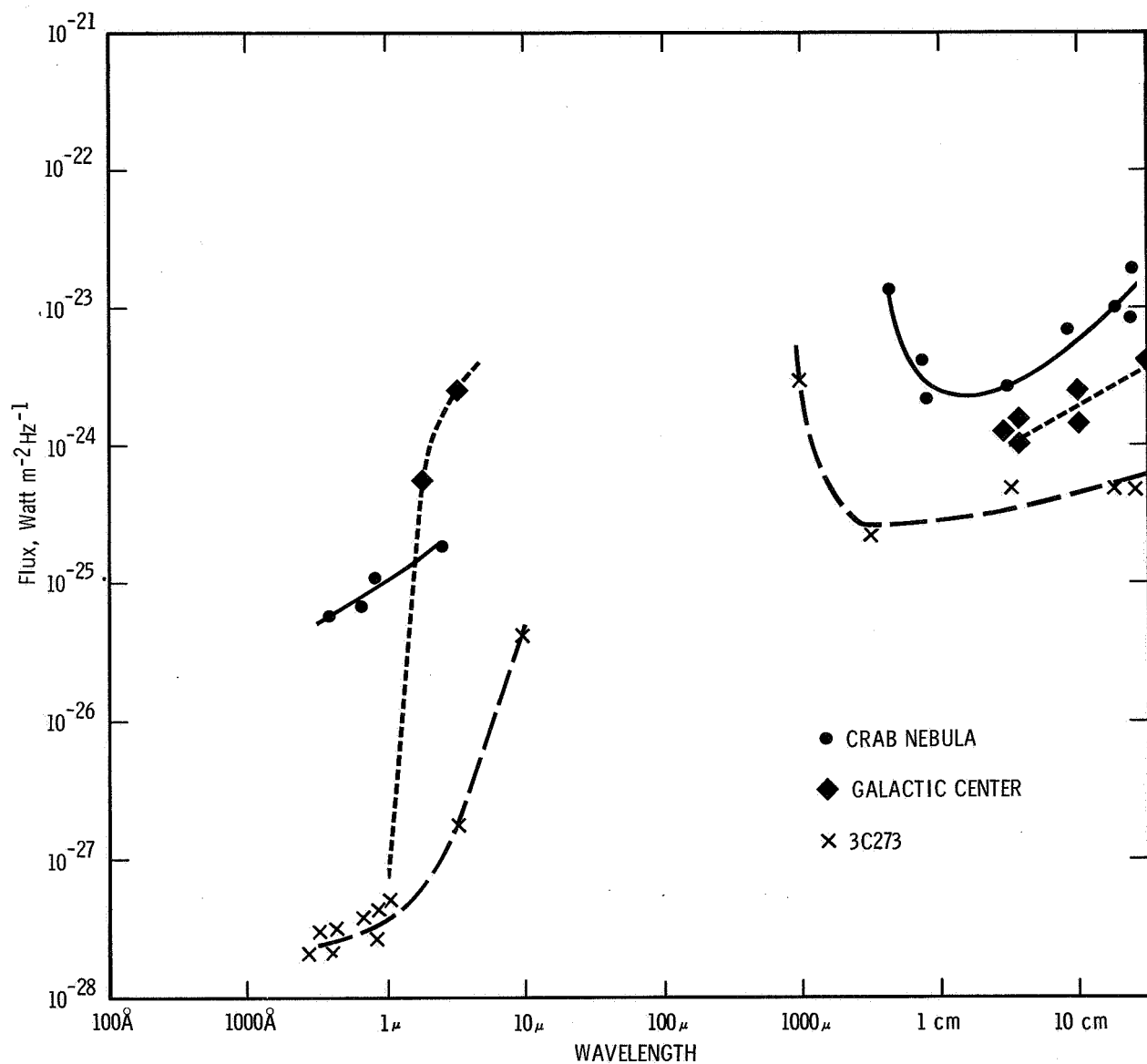


Figure 1.- Examples of submillimeter research needs in cosmology  
(Flux Measurements on Three Objects)

A strong impact on the development of the space sciences can also be expected from spaceborne submillimeter studies of the Sun where object energy and detector sensitivity pose less stringent instrumentation problems than in cosmological experiments. As to the urgency of solar physical work in the submillimeter band in general, the "Directions for the Future" by the Space Science Board of the National Academy of Sciences/National Research Council (ref. 2, pp. 180 and 221) states flatly, "Our ignorance of this region is almost complete" and "in the (solar) infrared, the present need is for any information whatever at wavelengths between 3 and 300 microns."

Of course, one is inclined to think first of closing the well-publicized submillimeter gap in the solar spectrum. Indeed, today the submillimeter spectrum of the Sun is known in no more than its rudimentary structure. Even this limited knowledge is essentially based on a combination of speculative laboratory experimentation and theoretical studies founded on a number of controversial atmospheric models. Whatever directly measured spectra are available exhibit but coarse spectral resolution or cover only minimal spectral bands in a handful of narrow spectral windows. Even then, since all measurements of this kind have been made from ground-based -- at best, airborne -- stations, they have been distorted under the influence of the radiometrically undefined -- and so far undefinable -- atmosphere over the measuring instrument. The consequence of this fact is that to date no reliable data on the solar energy and its spectral distribution in the submillimeter region exist.

Only from space can one expect to overcome these atmospheric difficulties which are peculiar to the submillimeter waves and which, to a large extent, are also responsible for the generally poor status of the knowledge in the submillimeter sciences.

Once the decisive step into space has been made and the solar spectrum has been isolated and measured, however, other key problems will come closer to their solution.

For example, it will at least become possible to locate the still undetermined minimum of the solar brightness temperature in the submillimeter band which, because of its suspected stability, might, in turn, be suitable for use as a reference point for many other kinds of astronomical measurements. Experimentation over an extended period of time will be required to confirm the assumed stability of the energy minimum. Figure 2\* shows that data on the solar brightness temperature are available on both sides of the submillimeter region, but that they are conspicuously absent inside the region itself.

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\*Figure 2 incorporates refs. 5, 18-30.

Another important example of needed solar submillimeter research concerns the question of the neutral solar limb or, respectively, of the wavelength where neither limb darkening nor brightening occurs. Considerable controversy has been centered around this problem, since important decisions about the validity of existing solar models and of the structure and compositions of the solar atmosphere depend on data of this kind. For example, Noyes (ref. 13) placed the neutral limb at about 50 microns, the report of the Space Science Board at about 1 mm. Only direct measurements from space at a variety of wavelengths will be able to settle this important question. Figure 3, which shows theoretically determined energy output profiles across the solar disk for different spectral regions, is taken from Noyes' paper.

The Space Science Board also points out the necessity of measuring the submillimeter spectrum of sunspots. No data on the molecular spectrum of these important solar features are as yet available. Interesting studies might become possible and unsuspected phenomena might be discovered when suitable submillimeter instrumentation is mounted on spaceborne observation platforms.

There are also hopes that submillimeter studies will assist in establishing in better detail the propagation history of solar outbursts on their path through the outer layers of the Sun. Since certain wavelengths can be associated with particular altitudes above the photosphere, disturbances in the emission at these wavelengths indicate the transition of the outburst through layers at these altitudes. In this way solar physicists are able to derive important facts on the radiative structure of these solar layers, and from time differences between transitions, the velocities of the bursts. An example of such a history is given in Figure 4, which has been taken from R. J. Coates' paper (ref. 14) and which distinctly shows such time differences in the emissions at three different wavelengths or altitudes, respectively. Measurements at submillimeter frequencies would add another time interval to the sequence.

From thermal submillimeter measurements of lunar and planetary surfaces it will further be possible to deduce some of their electrical properties (ref. 9). If combined with polarization studies, such experiments can also be used to study the surface composition of the moon or the planets (ref. 15). A series of moon-based submillimeter experiments has also been discussed in connection with the Lunar Exploration System for Apollo (ref. 16).

Measurements of the absolute solar submillimeter spectrum will, finally, benefit ground-based astronomical experiments. As Gaitskell et al (ref. 17) have demonstrated, worthwhile and meaningful experiments of this kind are indeed possible, even from sea level, if one is willing to accept a number of difficulties,

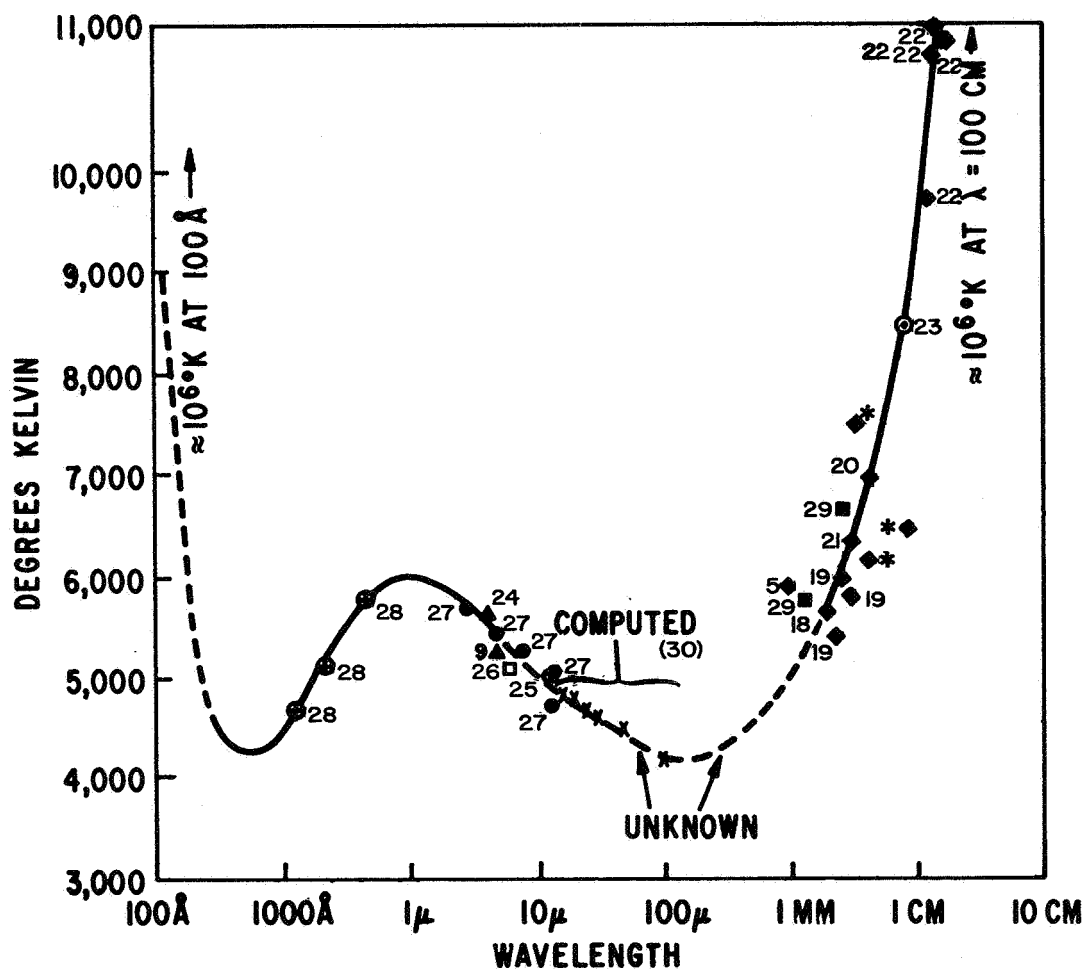


Figure 2.- Solar brightness temperatures as a function of wavelength (The identifying numbers near the curve are keyed to refs. 5, 18-30.)  
 \*Personal communication, C. W. Tolbert, 1966.

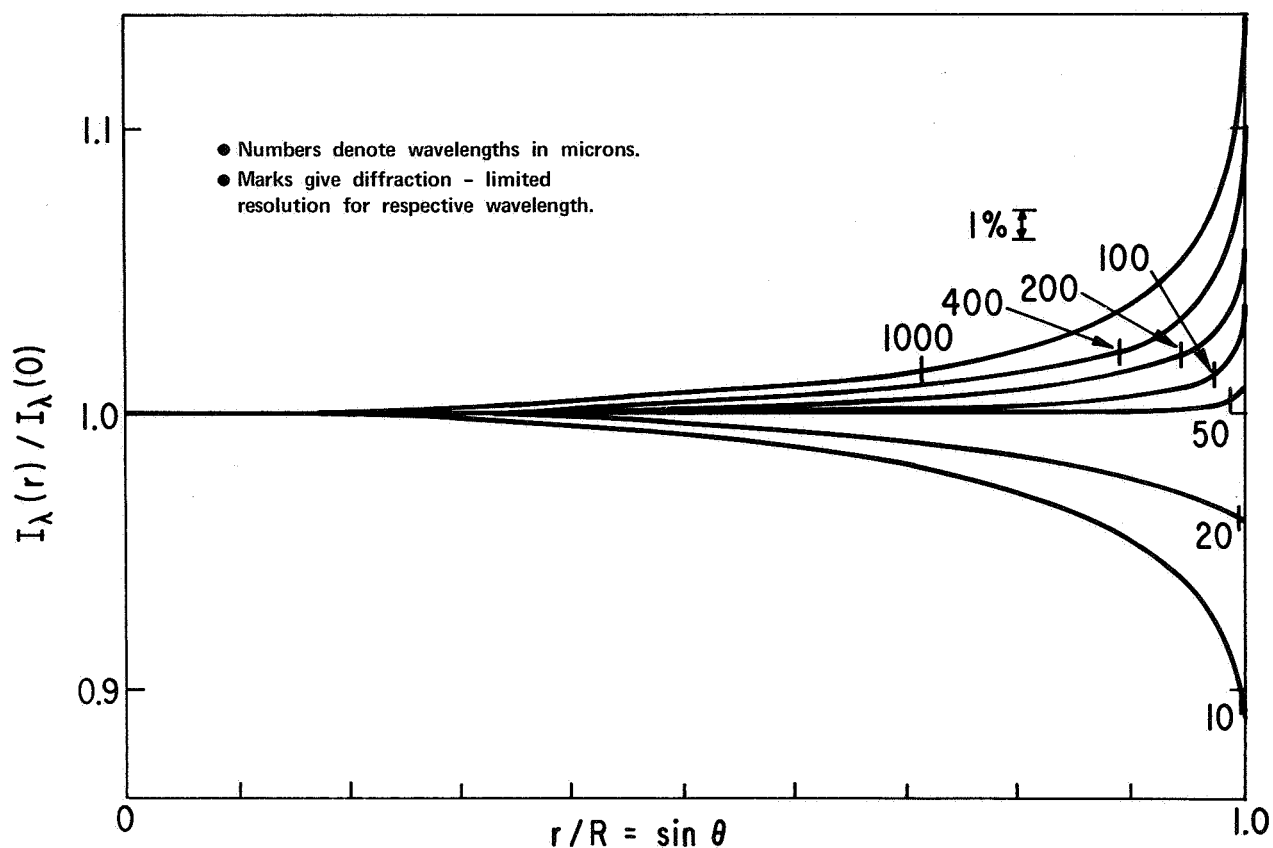


Figure 3.- Center-to-limb variation of the solar continuum predicted by the BCA model for various wavelengths in the infrared (ref. 13).

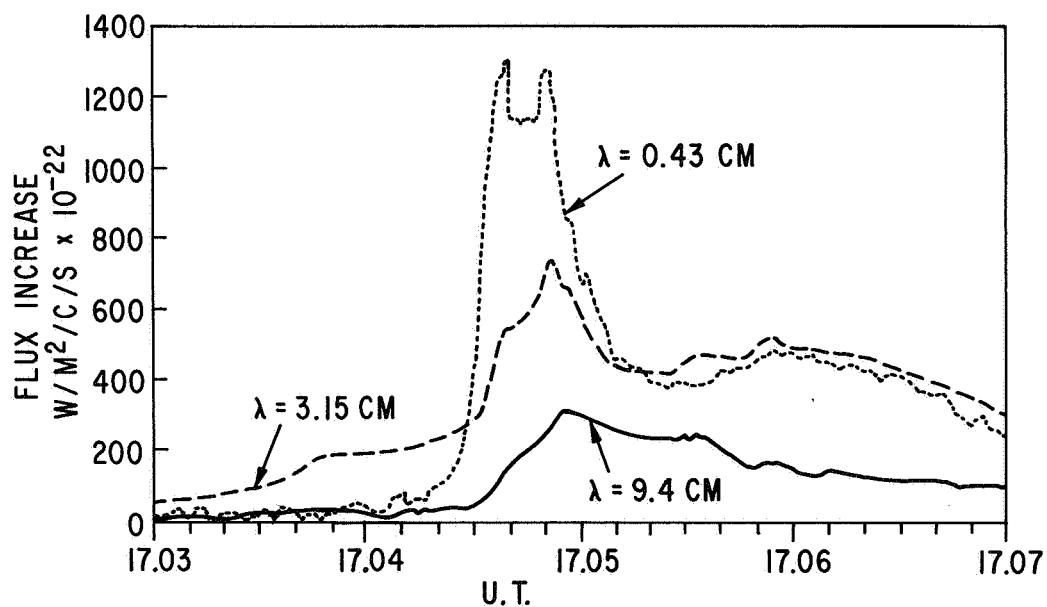


Figure 4.- Propagation history of a solar outburst through the solar atmosphere (ref. 14, p. 471)

and if one takes the appropriate precautions in the evaluation of results obtained.

Since solar spectral data could furthermore serve as a basis for the calibration of the terrestrial atmosphere, these experiments might also result in absolute thermal flux measurements on the ground and will certainly become further useful in the study of the atmosphere itself. Making use of the heavy absorption of submillimeter radiation by water vapor, such studies could conceivably help in the analysis of the extreme upper atmosphere and maybe in resolving some questions of any weak water vapor layers there.

A more detailed list of astronomical submillimeter problems of this kind -- many of them involving a multitude of individual experiments -- has been compiled from recent literature and is presented in Appendix A.

Important applications of submillimeter waves lie also ahead outside the purely scientific disciplines, notably as part of spaceflight operational activities of the future and, particularly, where use is made of the intermediate resolution associated with submillimeter optical systems. This is specifically the case when -- because of fundamental principles of physics -- microwaves fail to discriminate sufficient optical detail and when, on the other hand, for the same reason visible and infrared methods would require hypersensitive and delicate instrumentation, either in order to bring an object into the field of view of an instrument or to keep it there.

Searching for cold, dark, and small spaceborne objects is a point in case. An elaborate scanning system would often be necessary in such search activities, if visible radiation were used to survey a field that otherwise could effectively be covered with a fixed non-scanning submillimeter beam. Even if both the submillimeter and the visible beam were used in a scanning mode, the resulting reduction in scan time would roughly be inversely proportional to the wavelengths involved, typically, therefore, by a factor of  $10^2$  to  $10^3$ . Likewise, in tracking operations, the probability of losing a target would be smaller by three orders of magnitude, if compared with visible-light tracking; and correspondingly higher target velocities and directional change rates could be accommodated, while still considerably higher positioning accuracies could be attained than would be possible with microwaves.

In contrast to passive, detection-oriented applications for which the basic technology became available in about 1960, the beginnings of active submillimeter techniques are tied to the introduction of coherent submillimeter radiation sources which,

for all practical purposes, came about no earlier than 1964. An additional determined effort, both in research and engineering, is therefore needed in order to eliminate this 3-year lag and to fully develop the potential inherent in active submillimeter methods.

Precision pointing with visible light beams -- for example, for linking up the terminals or relay points of optical deep space communication nets -- could be simplified and considerably accelerated when an auxiliary, essentially boresighted, submillimeter system is used in a preliminary rough-pointing step. The 100- to 1000-fold search time reduction and beam-hold capability would also apply here, as it would to other flight operational functions, such as beam-ride guidance or tracking of reflectors mounted in cooperating vehicles.

Finally, in the area of optical communications proper, the opening up of the submillimeter region would make available from several hundred to several thousand new separable communication bands (the actual figure depending on where the limits of the overall band are placed and what bandwidth resolution one is willing to accept as the attainable state of art). It also promises a communication capability combining uniquely the high point-to-point energy transfer efficiency, privacy, and compactness of equipment that is peculiar to small wavelengths, with the relaxed beam-finding and link-up requirements associated with low-frequency operation. Also, the technology of transmission, reception, and antenna control can be based on the well-established and well-understood principles of optics and can, at the same time, take advantage of the high level of development in the RF and microwave areas, notably with respect to coherence and wave analytical techniques. Submillimeter communication therefore has its own merits and, accordingly, will take its own place and function within the space program.

The advantages of optical communications over communications using long wavelengths have often been discussed; recently, for example, by a group of the Hughes Aircraft Company (ref. 32) under contract to the NASA Goddard Space Flight Center. A figure of merit which compares the generalized communication theoretical potential of all wavelengths is given by

$$M = \frac{(S/N) \cdot BR^2 hc^2}{A_T A_R P_T L L_f}$$

where

S/N = signal to noise ratio  
B = bandwidth  
 $P_T$  = transmitted power  
 $A_T$  = area of transmitter antenna  
 $A_R$  = area of receiver antenna  
R = operating distance  
L = system loss factor  
 $L_f$  = frequency-dependent loss factor  
h = Planck's constant  
c = velocity of light.

M can essentially be understood as a figure representing the product of signal quality and signal quantity obtained per watt of transmitted power  $P_T$  and distributed into a solid angle of 1 steradian. The signal quality is assumed to be characterized by S/N and the signal quantity by the bandwidth B.

For ideally loss-free operation ( $L = L_f = 1$ ), the figure of merit becomes

$$M_o = \frac{f}{1 + (e^{hf/kT} - 1)^{-1}}$$

where k = Boltzmann's constant and T the temperature of a source displayed against a 0°K background. Figure 5, which is taken from the Hughes report, illustrates the inherent potential advantage of optical frequencies over microwaves. Having a source temperature of 100°K and 2300 MHz, which is the current operating frequency for deep-space communications as reference quantities, the advantage for submillimeter waves amounts to a factor of  $10^5$ .

Compared with visible light, this is still inferior by a factor of 1000. However, provided that good judgment is made as to where and when submillimeter waves should be used; e.g., as to operation in loss-less space, low-temperature source, scan time, small cost for large-aperture systems, and the like, the optimal operating point for communication purposes can, and often will, shift into the submillimeter region, if the appropriate technology is available. This last condition is still not fulfilled and indeed is in many instances only in the very first phases of basic research. In the light of the great potential offered, it appears important, therefore, to attack the still



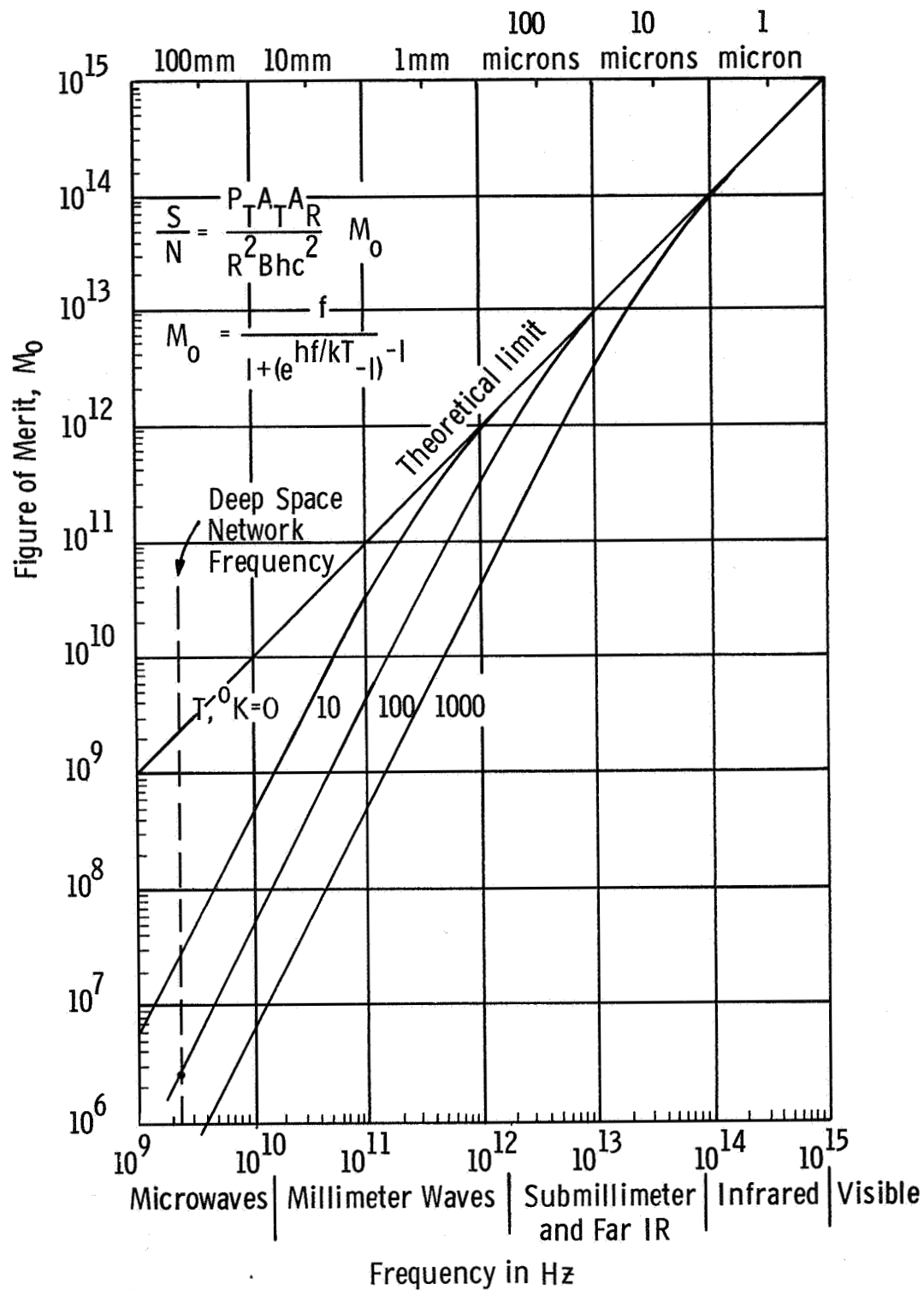


Figure 5.- Ultimate system figure of merit versus frequency

prevailing roadblocks which at this time are most noticeable in the areas of beam modulation and tuneable submillimeter sources. Promising starts have been made even in these most critical areas, however, and with a reasonable effort also these remaining problems will be solved.

Having discussed the expectations placed on submillimeter waves by the scientific and technical community, it appears in order to consider the state of the art of knowledge and to describe what is being done to fulfill these expectations.

## HISTORICAL BACKGROUND OF SUBMILLIMETER RESEARCH AND TECHNOLOGY

Under the definition given in the introductory paragraph, the beginning of submillimeter wave research reaches back to H. Rubens (ref. 33) when he succeeded in identifying and measuring theoretically predicted reststrahlen radiation in the 100-micron region, from NaCl (rocksalt) and KCl (sylvine); and it is interesting to observe that many essential elements of the submillimeter technology in use today were already available at the turn of the century.

Platinum strip bolometers (ref. 34), thermopiles (ref. 35), and thermocouples -- the latter in the configuration of a micro-radiometer (ref. 36) -- were used as detectors; rare-Earth burners and quartz-mercury lamps served as primary sources of radiation; and grating spectrometers using metal gratings (ref. 37), later supplemented by echelettes (ref. 38), were employed for wavelength separation. Interferometric methods were adopted for use in the far infrared by Rubens and Hollnagel (ref. 39) and Ignatieff (ref. 40), and quartz was the filter material preferred for short-wavelength cutoff while quartz mirrors and platinum wire grids were employed for polarization experiments (ref. 41). By 1925, Nichols and Tear (ref. 42) were able to separate and measure the emission of a quartz-mercury lamp at 420 microns, using black paper and quartz glass as filter materials. Some of the almost forgotten techniques, e.g., band separation by total reflection at a quartz-air or rocksalt-air interface by Jentzsch and Laski (ref. 43), have now deservedly been revitalized (ref. 44). The first reported penetration into the submillimeter region from the direction of the microwave region came in 1922 by Nichols and Tear who produced a discharge between very small wire oscillators. The smallest fundamental wavelength reached was 1.8 mm, while interferometric analysis revealed harmonics at wavelengths down to 0.8 mm.

As an interesting side issue, one may see, even from this historical account, why the submillimeter sciences are today

largely considered an optical -- as opposed to microwave or radio frequency -- discipline and why therefore most of the submillimeter research today is conducted in optical rather than electronic laboratories, although important submillimeter techniques have their origin in the microwave domain. In view of a lively controversy still going on about where to locate the submillimeter region, Appendix B, which contains a number of references justifying the currently prevailing practice, is presented.

While, subsequent to the initial period, submillimeter techniques became indispensable for the molecular spectroscopy of materials, this use remained virtually their only practical application. It is beyond the scope of this report to survey the application of submillimeter waves in this area.

The severe opacity of the atmosphere to submillimeter waves -- attenuations between 79 and 118 dB/km at 600 GHz were measured by S.Y. Chang (ref. 45) -- left little chance for the expansion of the application and utility of the art outside the laboratory. Other basic obstacles were the very long response times and low sensitivities of the detectors used and the non-availability of suitable cooling techniques. As a consequence, the interest in the submillimeter region restricted itself to rather straightforward refinement and mechanization of the basic instrumentation. Except for the invention of a more sensitive and faster pneumatic submillimeter detector in the form of the Golay cell (ref. 46) and, more recently, the emergence of powerful Fourier interferometric techniques, hardly any important development occurred to revive it.

#### STATE OF THE ART OF SUBMILLIMETER TECHNOLOGY

Together with the implementation of the space program itself, the most important factor stimulating new interest in the submillimeter range was the development of detectors that were not only faster and more sensitive, but which, after some additional development, could be expected to withstand the rigors of the launch and to be suitable for unattended operation in the newly accessible space environment.

In fact, an entire class of fast and efficient solid-state submillimeter detectors appeared. Among them were the super-cooled, antimony-doped germanium detector, the sensitivity of which extended to 135 microns (ref. 47); the impurity photo-conductor detectors, notably Putley's (ref. 48) indium antimonide detector; the gallium-doped germanium bolometer (ref. 49); and the so-called "hot-electron bolometer" which is based on direct absorption of radiation by the free electrons of a semiconductor

(ref. 50). The latest representative of this class is the super-cooled point contact detector, which is obtained by pressing together two pieces of wire -- In, Pb, and other materials (refs. 51, 52). It is still uncertain whether the point contact itself or the natural oxide layer of the material -- the latter forms a dielectric barrier capable of passing a "zero-voltage" current -- is the active element in the detector (ref. 53).

As shown in Table I, the new submillimeter detectors now offer sensitivities better by a factor of 1000 over those available a decade ago. In the same period the all-important time constants have been improved by four to five orders of magnitude. The Josephson detector, for example, in its original In-In configuration and at  $2.2^{\circ}\text{K}$  has an N.E.P. of about  $5 \times 10^{-13}$  watt  $\text{Hz}^{-\frac{1}{2}}$  and covers a range from about 200 to 3000 microns with a peak at 2000 microns, at a time constant at sub-microsecond, possibly sub-nanosecond, levels. Its response characteristics change depending on the materials used. Aside from In-In, also Nb-Nb, Pb-Pb, Ta-Ta, and Nb-Ta are being studied as point contact detectors (ref. 53).

Recently, new submillimeter detectors have been proposed in the form of superheterodyne quantum receivers, more accurately called down-converter-maser-superheterodyne receivers (ref. 54), in which metal-doped crystals are used as principal detection agents. Chromium-doped cyanite ( $\text{Cr}^{3+}:\text{SiO}_2\text{Al}_2\text{O}_3$ ) supposedly is useful for wavelengths upwards of 150 microns, while nickel-doped titania ( $\text{Ni}^{2+}:\text{TiO}_2$ ) and vanadium-doped sapphire ( $\text{V}^{3+}:\text{Al}_2\text{O}_3$ ) can be employed at wavelengths  $>600$  microns. Time constants  $<10^{-7}$  sec are considered possible. Since none of these detectors seems to have been demonstrated in actual applications, they have not been listed in Table I, however.

Along with the detectors, important advances towards solution of the crucial associated cooling problem were made. The NASA Electronics Research Center played an important role in this development.

The most effective solution of the cooling problem would obviously be the development of detectors that can be operated at room temperature. An early detector of this kind is the tungsten cat whisker which was found useful for laboratory experiments in the 1 mm range (ref. 55). The mechanical delicacy of the detector and associated waveguide system, the low general radiometric sensitivity, and difficulties encountered in adjusting the response to submillimeter wavelengths have so far excluded the tungsten whisker from serious consideration for space experiments. Another attempt at a room temperature submillimeter detector, this time with emphasis on ruggedness, was made by the Airborne Instruments Laboratory of Cutler-Hammer, Inc., under a contract with

the NASA Electronics Research Center (ref. 56). Two broadband thermal detectors, both using thermistor bolometers behind a suitable absorber, resulted from this contract. Although the mechanical stability of the detectors is indeed remarkable, their marginal radiometric performance excludes them from use in space except, possibly, in low-rate, high-energy level applications (see Table I).

In another effort, ERC is searching for new cooling techniques for space applications. The purpose of this work is to circumvent the operational hazards of the conventional closed-cycle, liquid coolant systems which, while well understood, generally are bulky and mechanically too complex to be reliable and which, at the same time, place high demands on the electrical system of a spacecraft. Therefore, the less complex open-cycle systems -- mostly using solid rather than liquid coolants -- and passive coolers are being considered for space use. The passive cooler essentially consists of a series of extremely well-insulated pan-shaped radiators nested into each other and exposed to the radiation of space by large blackened "guard" flanges. Another promising approach is now taken through an ERC grant to the Stevens Institute of Technology under which cooling effects by gas desorption from porous adsorbents are being investigated using charcoal, zeolite, silica gel alumina and other material as adsorbents. In an optimal case, a temperature reduction from 8°K to 2.6°K has been obtained at an initial pressure of 1 atm using 3 grams of adsorbent. Preliminary results on heat loads handled by this method are encouraging and research is therefore continuing (ref. 57).

Physicists are now confident that a hybridized system consisting of an open-cycle Ar-CO<sub>2</sub> cooler and/or the passive space radiator, in combination with a second, gas-desorption stage, can be developed to maintain one-digit Kelvin temperatures over useful periods of time, especially if intermittent operation is permissible. Except for valves, virtually no moving parts would be necessary in such a hybridized system.

A developmental closed cycle liquid helium cooler could carry a heatload of about 1 watt at 40°K at a needed power of about 2000 watts. For mechanical refrigeration at 77°K the corresponding figures are 2 and 100 watts. In comparison, at the present state of the art, the solid argon-carbon dioxide cooler itself could handle a heatload of 25 mW and maintain temperatures below 50°K for 1 year in a 300°K environment. The system would weigh about 14 kg (30 lbs) and would require about .048 m<sup>3</sup> (1.7 ft.<sup>3</sup>) of space. Essentially, the amount of solid coolant carried determines the capability of the cooler. A 50-cm diameter passive space radiator which can be part of the system may dissipate 20 mW emanating from a source having a temperature of 40°K.

**TABLE I**  
**SUBMILLIMETER DETECTORS**

Detector	Typical Operating Temperature	Typical Figures of Merit		Typical Performance <sup>1)</sup>			References
		Jones' M <sub>2</sub> <sup>2)</sup>	D* <sup>3)</sup>	Spectral Range (microns)	Time Constant (sec)	Noise Equivalent Power, NEP <sup>4)</sup>	
Thermocouple	300 °K	0.85)	1 x 10 <sup>9</sup>	< 50	4 x 10 <sup>-2</sup>	5 x 10 <sup>-11</sup>	58
Perkin-Elmer	300 °K	2	—	0.5 to > 1000	7 x 10 <sup>-3</sup>	3 x 10 <sup>-12</sup>	46
Golay Cell	2 °K	29	—	to 2000	1 x 10 <sup>-2</sup>	6 x 10 <sup>-12</sup>	58, 59
Carbon Bolometer	3.7 °K	200	—	< 1 to > 1000	1 x 10 <sup>-3</sup>	1 x 10 <sup>-12</sup>	59, 60
Superconducting Bolometer	2.15 °K (1.80 °K) <sup>6)</sup>	2300	—	> 10 to > 1000	4 x 10 <sup>-4</sup>	5 x 10 <sup>-13</sup> (7 x 10 <sup>-14</sup> , 6)	5, 60-64
Ge-Ga Bolometer	4.2 °K	—	—	50 to 135	< 10 <sup>-5</sup>	—	47
Ge-Sb Photoconductor	1.5 °K	—	2 x 10 <sup>11</sup>	200 to 8000	2 x 10 <sup>-7</sup>	< 1 x 10 <sup>-10</sup>	48, 61
InSb Impurity Detector (Putley)	4 °K	—	—	500 to 8000	1 x 10 <sup>-3</sup>	5 x 10 <sup>-13</sup>	65
Wideband InSb Impurity Detector, Cooled Transformer	4 °K	—	—	150	1 x 10 <sup>-7</sup>	1 x 10 <sup>-11</sup>	65
Narrow Band Impurity Det.	< 5 °K	—	1 x 10 <sup>11</sup>	100 to 1400	1 x 10 <sup>-7</sup>	5 x 10 <sup>-13</sup>	66
Ge-B Impurity Detector	2.2 °K	Not applicable (effective area is indeterminate)	2.5 x 10 <sup>12</sup>	300 to 10000	3 x 10 <sup>-7</sup>	5 x 10 <sup>-13</sup>	50, 59, 67
InSb Electron Bolometer	15 °K	Not applicable (effective area is indeterminate)	Not applicable (effective area is indeterminate)	300 to 6000	< 1 x 10 <sup>-8</sup>	5 x 10 <sup>-13</sup>	52, 53
Josephson In-In Point Contact Detector	Room Temperature	—	—	100 to 200	—	—	55
Josephson Nb <sub>3</sub> Sn Detector	Room Temperature	—	—	> 100	3 x 10 <sup>-7</sup>	6 x 10 <sup>-7</sup>	55
Tungsten Cat Whisker/IN23 Silicon Pellet	Room Temperature	—	—	> 100	3 x 10 <sup>-7</sup>	9 x 10 <sup>-9</sup>	56
Same Pulsed Detection with Lock-In Gating System	Room Temperature	—	—	10 to 6000	1.0	10 <sup>-8</sup>	56
Broadband Submillimeter Thermistor Bolometer	Room Temperature	—	—	10 to 150	6 x 10 <sup>-3</sup>	5 x 10 <sup>-10</sup>	56
AC Submillimeter Thermistor	Room Temperature	—	—	—	—	—	56

1) Performance data stated are not necessarily reliable to given M<sub>2</sub> and D\*.

2) M<sub>2</sub> = 2.12 x 10<sup>-10</sup> A<sup>1/2</sup> f<sup>1/2</sup> (NEP)<sup>-1</sup>  
A = effective area, f = bandwidth

3) D\* = A<sup>1/2</sup> (NEP)<sup>-1</sup>.

4) Generally in watts, but not necessarily reduced to unit bandwidth or area. References should be consulted for details.

5) M<sub>2</sub> and D\* given by different sources.

While thus the development of cooling techniques is progressing, it must be kept in mind that, first, without an efficient cooler, spaceborne submillimeter science would virtually be impossible, and, second, that all of the above systems would still require an intensive effort to make them fully space-qualified.

An impulse decisively affecting the capabilities in the area of optically active operations -- pointing, tracking, guidance, communications, and the like -- came from the emergence of new high-powered sources of coherent radiation in the submillimeter range. While the CSF carcinotron approached the region from the microwave direction and reached 350 microns, Gebbie's cyanide and water vapor lasers (ref. 68) did so from the optical side, attaining 337 microns and thus closing the gap between the infrared and microwave portions of the spectrum. At 337 microns, where a number of different molecules have been found to lase, pulsed power outputs up to about 100 watts have been reached by Stafsudd and his co-workers (ref. 69) with a methane-nitrogen mixture. There is mounting evidence that  $H_xCN$  is the real active species in the system (refs. 69, 70). Optical lasing has meanwhile been achieved at many spectral lines out to almost 800 microns. An additional number of potential submillimeter laser frequencies has been identified by Coleman (ref. 71). In some cases, cw operation has been demonstrated at acceptable power outputs.

The rather ambitious goal to develop a tunable submillimeter laser is now being attacked through a NASA-ERC project in which a semiconductor (or semimetal) bulk laser is being investigated for suitability as the basic generator. Tuning is to be done by magnetic fields at liquid nitrogen temperatures, and pumping by means of a 10.6-micron  $CO_2$  laser. A bismuth-antimony alloy is to be used as laser material.

Recently, proposals have been made to develop a tunable coherent source using the interaction between the backward waves originating in certain strongly birefringent crystals, such as selenium, in their excited state (ref. 72). The output of such a system would generally be in the infrared and, by changing the direction of propagation, would be tunable over a wide range, e.g., 7 to 40 microns for selenium, depending on the pumping frequency employed. The operating wavelength could be much longer in other materials. An important operational aspect of this approach is that, by principle, coherence of radiation is here achieved without optical cavities and that therefore the internal alignment of the apparatus might become comparatively simple.

Table II reviews the current state of submillimeter wave generation and gives the references which should be consulted for details. One sees that also outside the 337-micron band power outputs in the order of watts have been obtained at a number of frequencies. Progress is also being made regarding the gain or, respectively, the length of the laser cavity which initially was on the order of 7 to 10 m, but which now has become smaller (1-3m) and manageable even by spaceflight standards foreseen for the '70s. For example, the CH<sub>4</sub>-N<sub>2</sub> laser by which 100 watts of output were obtained was about 2.5 meters long. Operational difficulties are still apparent from the generally low efficiency, however, which for the entire system is still on the order of 10<sup>-5</sup> to 10<sup>-6</sup>.

Figure 6 contains output data and spectral distribution of laser generators reported through 1967 and for comparison, also of the classical incoherent submillimeter sources and of a black-body at 5000°K, which is the estimated median temperature of the Sun for the submillimeter range.

Meanwhile, also other methods of submillimeter wave generation have been investigated. From this work, a number of new spectral bands have become available, although at power levels that are not useful for other than spectrometric purposes. Thus, by carcinotron mixing, wavelengths down to 311 microns (ref. 73) and 259 microns (1160 GHz) have been reached (refs. 74, 75), while Woods and Strauch (ref. 76) and a NASA/ERC/MIT team claimed to have generated 160 microns and 91 microns, respectively (ref. 73).

Another approach to submillimeter wave generation has finally been pointed out by Langenberg et al (ref. 77). They are using Josephson-type supercooled tunnel junctions and predict that an output of about 1 mW of radiation can be obtained by a single junction if In, Pb, or Pb-Bi combinations are used. Wavelengths generated with this arrangement so far include 860, 460, and 370 to 300 microns.

Because of the inherently low power levels and very restrictive efficiencies (0.01 to 0.1 percent) obtainable with these exotic generators, and because of the costliness and the mechanical delicacy of the generators themselves, an attempt is now being made through an ERC in-house effort to develop a rugged, solid-state, transistor-type generator for the 1-mm range by which efficiencies in the vicinity of 10 percent band power levels approaching 10 mW are ultimately expected. Until such devices can be made operational, it can well be assumed that the laser and the classical incoherent radiators will for some time remain the primary sources of submillimeter radiation useful for applications in space. A general review of the coverage of the



TABLE II  
SUBMILLIMETER LASERS

Wavelength (microns)	Origin	Power Output W *	Tube Length (meters)	References
71.4	D <sub>2</sub> O	< .1	5	70
72.0	D <sub>2</sub> O	0.008	5	87
72.4	D <sub>2</sub> O	0.02	5	87
72.7	D <sub>2</sub> O	$8 \times 10^{-2}$	5; 7; 9	68, 70, 87
73.3	D <sub>2</sub> O	0.04	5	87
73.4	H <sub>2</sub> O	$2 \times 10^{-3}$	5	70, 87
73.5	D <sub>2</sub> O	< .1	5	70
74.5	D <sub>2</sub> O	0.04	5	87
76.3	D <sub>2</sub> O	$9 \times 10^{-3}$	5	70, 87
78.1 - 79.1	H <sub>2</sub> O	$2 \times 10^{-1}$	5	68, 70, 84, 87
		$1.5 \times 10^{-1}$ cw	3	82
78.5	H <sub>2</sub> O	0.007	8.7	87
84.1	D <sub>2</sub> O	$2 \times 10^{-2}$	5	70, 87
		.1 cw	3	86
84.3	D <sub>2</sub> O	$5 \times 10^{-2}$	5	87
89.8	H <sub>2</sub> O	$6 \times 10^{-3}$	5	70
107.7	D <sub>2</sub> O	$1 \times 10^{-2}$ ; cw	5	70, 86, 87
115.4	H <sub>2</sub> O	$7 \times 10^{-4}$	5	70
118.1 - 118.8	H <sub>2</sub> O		5	70
118.7	H <sub>2</sub> O	0.001	5	87
120.1	H <sub>2</sub> O		5	87
126.2	(CH <sub>3</sub> ) <sub>2</sub> NH	1	5	87
128.8	(CH <sub>3</sub> ) <sub>2</sub> NH	1	5	87
131.0	(CH <sub>3</sub> ) <sub>2</sub> NH	1	5	87
135.0	(CH <sub>3</sub> ) <sub>2</sub> NH	0.2	5	
171.6	D <sub>2</sub> O	cw	2.1	86
181.9	D <sub>2</sub> + B <sub>12</sub> CN	.1	5	87
190.1	D <sub>2</sub> + B <sub>12</sub> CN	.1	5	87
195.0	D <sub>2</sub> + B <sub>12</sub> CN	$2 \times 10^{-2}$	5	87

\* Within factor 3 from given value

Continued—

TABLE II  
SUBMILLIMETER LASERS (Continued)

Wavelength (microns)	Origin	Power Output W*	Tube Length (meters)	References
201.2	(CH <sub>3</sub> ) <sub>2</sub> NH	5 x 10 <sup>-3</sup>	5	87
204.5	D <sub>2</sub> + B <sub>12</sub> CN	4 x 10 <sup>-2</sup>	5	87
211.1	(CH <sub>3</sub> ) <sub>2</sub> CN	0.04	5	87
220	H <sub>2</sub> O	2 x 10 <sup>-2</sup>	5	80
223.2	(CH <sub>3</sub> ) <sub>2</sub> CN	0.003	5	87
309.9	(CH <sub>3</sub> ) <sub>2</sub> CN	0.4	5	87
311.1	(CH <sub>3</sub> ) <sub>2</sub> CN	0.7	5	87
336 - 337	HCN	< .1 cw	9	68,83
	CH <sub>4</sub> +N <sub>2</sub>	100	2.5	69
	XCN	10.0	6.5	78
	CH <sub>3</sub> COCH <sub>3</sub> + N <sub>2</sub> or air	1.6 x 10 <sup>-3</sup> cw	3; 2.1	82,86
	CH <sub>3</sub> CN/C <sub>6</sub> H <sub>5</sub> CN			79
336.8	(CH <sub>3</sub> ) <sub>2</sub> CN	7	5	87
372.8	(CH <sub>3</sub> ) <sub>2</sub> NH	.1		81,87
537.7 - 538.2	ICN	5 x 10 <sup>-1</sup>	6.5	78
774	ICN		6.5	85
791 (2)	H <sub>2</sub> O	cw		86

\* Within factor 3 from given value

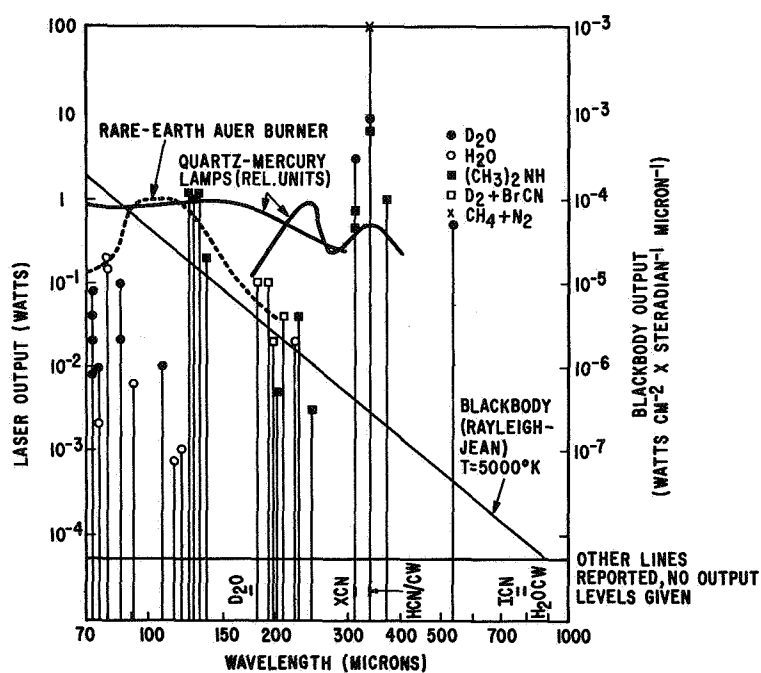


Figure 6.- Submillimeter radiation sources

submillimeter range by the various generating techniques is presented in Figure 7.

Significant progress has also been made in the area of submillimeter wavelength separation. Possibly following leads stemming from work in the early history of submillimeter reststrahlen, and possibly also from the observation that halide crystals become transparent again at long wavelengths, Yamada et al (ref. 88) measured the far infrared and submillimeter transmittance of a large number of reststrahlen filters which they used in the form of powders inbedded in polyethylene sheets. Among others, NaF, KBr\*, BaF<sub>2</sub>, LiF, NaCl, TlCl\*, TlI\*, and CaCO<sub>2</sub> were investigated. These filters can be employed, either by themselves or in combination, to produce short wavelength cut-offs at various wavelengths up to 200 microns. The gradient of the absorption curve was found to increase when finer powders and/or thinner layers were used. The gradients increased when the operating temperature decreased (ref. 90). Some of the reststrahlen materials are already routinely used as reflection filters for the same spectral region. Hadni (ref. 91) also fabricated band cutoff filters for the 90- to 150-micron range, with high transmittance on both sides, while Taub and Cohen (ref. 92) obtained beam-splitter or cutoff filter effects at 900 microns when fused quartz/air slabs were used in the form of suitably configured oversized waveguides.

Other, and possibly superior, substitutes for the powder-polyethylene filters are now becoming available and popular in the form of wire mesh filters with up to 11 wires per millimeter which provided an effective low-wavelength cutoff centered at 150 microns at a reflectivity gradient of 1.5 percent per micron wavelength. Generally, wire mesh filters eliminate radiation of a wavelength shorter than roughly 1.3 times the mesh constant (ref. 93). With wire grid filters used in transmission, highest effectiveness is obtained at wavelengths between 1 and 1.2 times the mesh constant, depending on construction (ref. 94). Figure 8 and Figure 9 show the transmittance characteristics of a number of powder and wire mesh filters.

Wire mesh filters are now often fabricated by modern electro-deposition and photoetching techniques (ref. 95) and are of a precision that makes them practical for narrow-band wavelength separation in interferometric spectroscopy. When grid patterns of various designs are used in sequence along the optical path, a variety of high-pass, low-pass, and bandpass filters can

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\*These, and some other materials, have been used as reststrahlen filters as early as 1913 (literature quoted in Schaeffer and Matossi (ref. 89)).

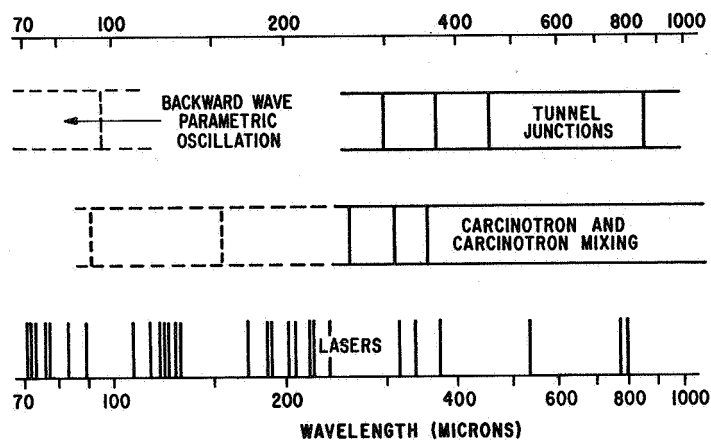


Figure 7.- Submillimeter generation (state-of-the-art, 1967)

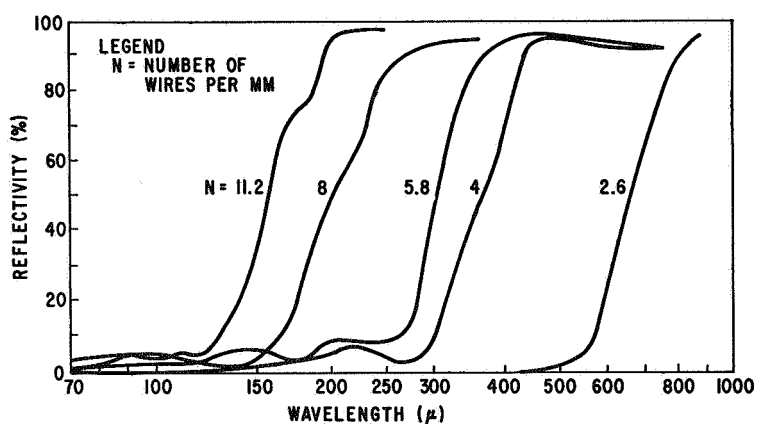


Figure 8.- Reflectivity of metal mesh filters (ref. 97)

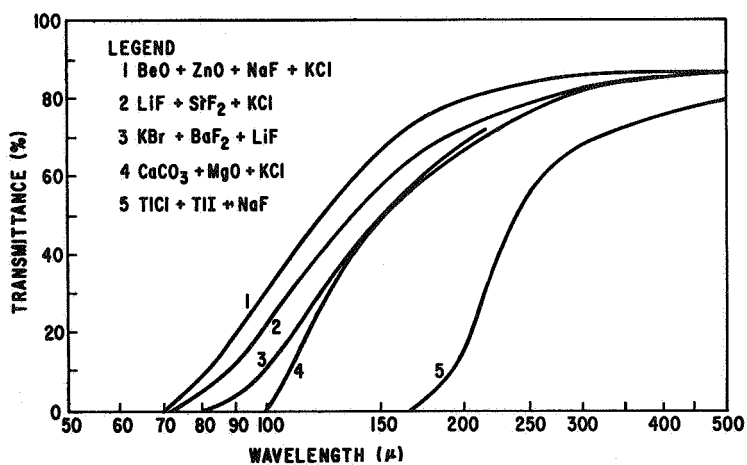


Figure 9.- Transmittance of various powder filters (ref. 88)

be obtained and absorption edge gradients of several orders of magnitude in distinct bands have been realized by the same author.

It can be foreseen that wire mesh techniques will increasingly replace crystal methods, both in wavelength separation and polarization applications. Meshes with 80 wires/mm can be produced, but the problems of filter flatness and wire parallelism will have to be solved before such fine mesh can compete effectively with more conventional means. A compact double Fabry-Perot interferometric spectrometer for the 200- to 1000-micron range, which is based entirely on wire mesh technology, is now under construction at the NASA Electronics Research Center.

The new fabrication techniques are also used in the construction of precision waveguides for submillimeter and millimeter wavelengths (ref. 96). Such wavelengths are becoming increasingly important in the matching of small detectors with their receiver optics which generally have a low resolution. It seems justified to assume that both the powder filters and metal grids will contribute significantly to spaceborne submillimeter spectroscopy, once they have been conditioned to withstand the rigors of the launch environment. NASA technologists are optimistic that this goal can also be achieved.

Little has been said so far on submillimeter receiver optics, largely because the problems in this area are rarely more than an extension of those valid for the visible and infrared regions and because progress will mostly depend on the emergence of new materials, fabrication methods, and control techniques. This applies particularly to refractive optics which, except for the use of some recent plastics in filters, for most practical applications still relies on the classical quartz technology. Reflection methods, in contrast, are benefiting much from the advances made in the conventional optical technology.

Since surface quality of submillimeter mirror optics is a less critical constraint than in optics for the smaller wavelengths, emphasis in submillimeter optical development can here be directed toward large apertures. The Space Science Board (ref. 2, p. 241) recommends studies into the feasibility of submillimeter telescopes with apertures in the order of 100 feet in diameter. Such large apertures will augment at the same time optical resolution, which declines linearly with wavelength and overall systems sensitivity, provided diffraction-limited performance is achieved, maintained, and indeed actually used during flight.

Theoretically, at a 500-micron wavelength, a 1-m diameter diffraction-limited mirror will resolve about 2 minutes of arc. An optimally matched, that is, round, detector 2 mm in diameter would require a relative mirror aperture of about  $f/3.5$  to achieve diffraction-limited resolution. These are figures attainable within the present state of the art.

Major efforts are underway in the large optics area under NASA sponsorship both in-house and through contracts; initial results in the control of segmented mirrors have already been obtained, and current work is now being extended toward figure control for flexible, thin, large mirrors.

Also in this important field, the demonstrated initial achievements give reason for confidence that, given time for development, the techniques will be practical in space applications. Meanwhile, mirrors and telescopes, while marginal in size, are judged sufficient to assure success for the initial pioneering projects in submillimeter astronomy.

#### STATE OF SUBMILLIMETER ATMOSPHERICS AND ASTRONOMICAL RESEARCH

Since this report limits itself to the consideration of experiments outside the laboratory, a review of past work and achievements in the areas of submillimeter research can be short. Up to the mid 1950's virtually no literature existed on atmospheric and astronomical research in the submillimeter range proper. In 1957, Gebbie (ref. 98) identified a number of atmospheric windows at about 360, 460, 620, 730, 860, and 1360 microns, while measuring the solar spectrum with a Michelson interferometer from an altitude of 3450 meters. Only 7 years later the Russians opened a new round of atmospheric experiments (ref. 99) largely confirming Gebbie's results, as later also did Williams and Chang under a NASA grant to Ohio State University (refs. 100, 101). In general, these measurements held up the assumption that atmospheric submillimeter absorption is mainly due to water vapor. Figure 10 shows the absorption calculated on the basis of this theory, as taken from a paper by J. A. Bastin (ref. 9). On the other hand, Figure 11, which is the result of an experiment by Boyle and Rodger (ref. 58) in the 100- to 200-micron range, demonstrates that calculations or laboratory experiments fail to do full justice to actual conditions and that, indeed, considerable detail may be gained by measurements in the field. Emphasizing the millimeter range where absorptions are less severe, Baldock, Bastin, et al (ref. 102) measured from 2860 m the lunar radiation at 800 microns and above with a Golay cell (refs. 102, 103). Farmer and Key (ref. 104) tried to determine the solar

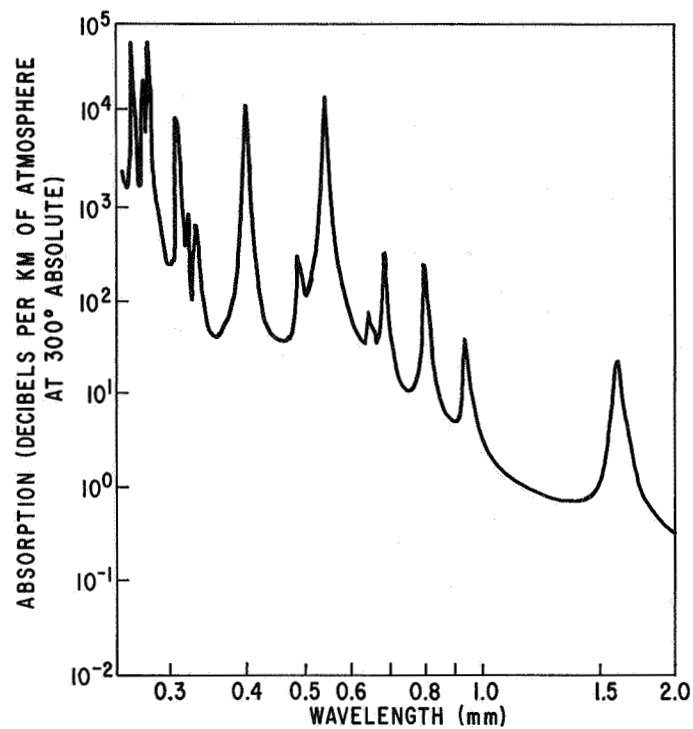


Figure 10.- Atmospheric absorption due to water vapor based on  $7.5 \text{ gm/cm}^3$  of precipitable water (ref. 3, p. 209)

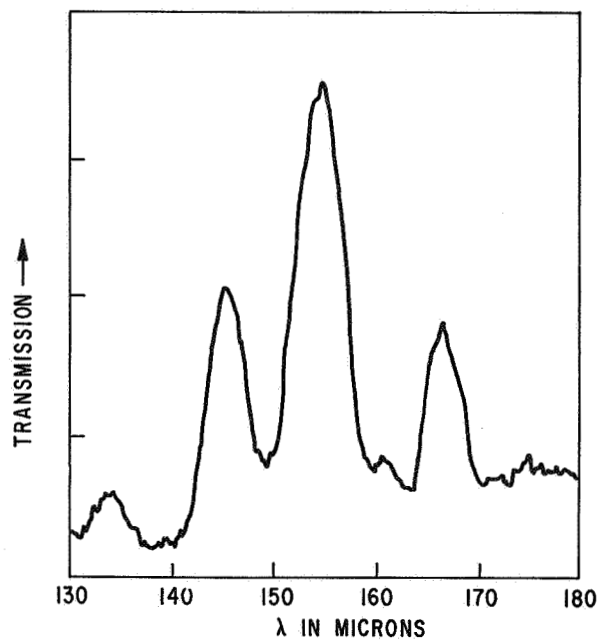


Figure 11.- Atmospheric absorption spectrum in the region of 150 microns (ref. 58, p. 69)

spectrum up to 400 microns with a Golay cell behind an f:7 Czerny-Turner spectrometer, but even at an altitude of 5200 m failed to find radiation between 40 microns and the window at 345 microns. The first continuous solar spectrum covering the entire submillimeter range -- actually the spectrum of a combination of solar and atmospheric emissions between 200 and 2000 microns -- was obtained by Gaitskell and Gear (ref. 105) using a 1.6-m Cassegrain telescope with a Fabry-Perot interferometer and a Golay cell on the Pic-du-Midi at an altitude of 2880 m (Figure 12). The resolution obtained was about 60 microns at the lower end of the wavelength region covered and 30 microns at the higher end. The authors were also able to measure the radiation from the moon through the 740-micron window.

Turning to weaker objects, but already using the more sensitive germanium bolometer and engaging the powerful Mt. Palomar 200-inch telescope, Low and his co-workers (ref. 5) succeeded in detecting the 1-mm radiation from the moon from the prominent quasistellar radio sources 3C273 and 3C279 (ref. 106) and from Mars.

Finally, as a step toward spaceborne submillimeter astronomy, a group at the NASA Goddard Institute for Space Studies under W. F. Hoffman (refs. 62-64) undertook the design of a balloonborne germanium bolometer and used the instrument in a program to detect and measure the submillimeter radiation from interstellar grains and other extended sources. Although the altitudes reached approached 10 km where most of the terrestrial water vapor would lie under the balloon, the overall sensitivity of the instrument (field of view 2 degrees, bandwidth about 60 microns peaking at 320 microns) was too low to detect other than the moon's radiation. Further flights with smaller fields of view and at shorter wavelengths are being prepared (ref. 63). A submillimeter astronomical telescope with a projected 75-cm aperture and with a capability for Coudé focus instrumentation is being constructed under a NASA Electronics Research Center contract with the Melpar Corporation, both as a test bed for submillimeter technology and as a research tool. Although this instrument is to be ground-based, plans have begun for a balloonborne telescope which will ultimately be used aboard a satellite.

#### NASA'S ROLE IN SUBMILLIMETER RESEARCH AND DEVELOPMENT

It is natural that a discipline whose main promise lies in its possible contribution to the space sciences would find a sponsor in the National Aeronautics and Space Administration. The earlier chapters of this report have already indicated that NASA supports a large number of programs in the area of submillimeter optical -- in particular, astronomical -- technology. This



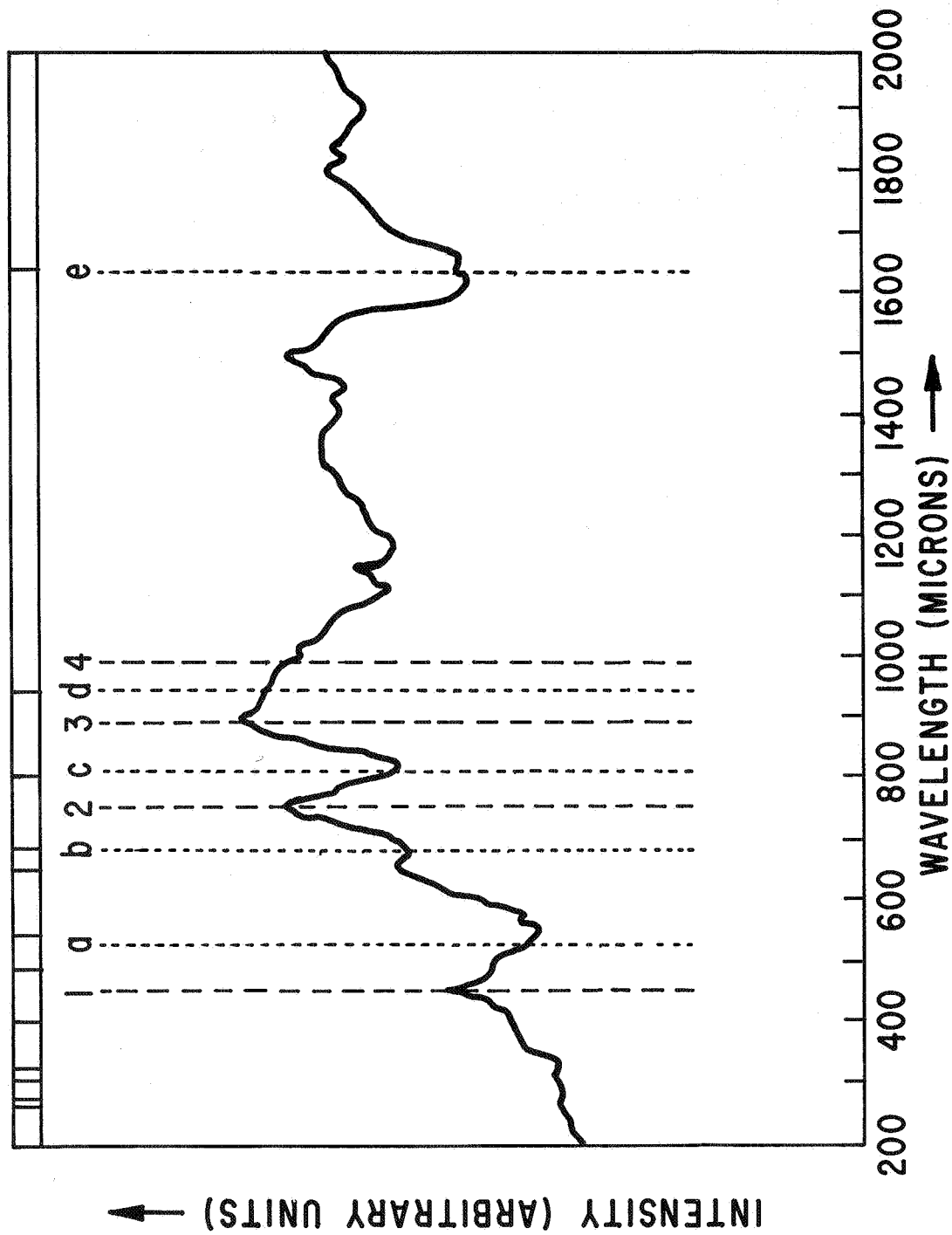


Figure 12.- Solar radiation as a function of wavelength; lines denote reference wavelengths (windows and absorption lines); principal water absorption lines are indicated at top of figure (ref. 105, pp. 237-244)

support is intended not only directly to outside groups actively engaged in the submillimeter sciences, but also through in-house work and contracts originated by NASA scientists. This way, NASA also provides help and encouragement to those sectors of the scientific community who could not, or who would not, wish to undertake a project unless the required technology were available.

Already, an impressive complex of submillimeter scientific capabilities has come into being at various Centers of the National Aeronautics and Space Administration, and it is fortunate that the activities of the NASA complex supplement the programs in the European countries in a most advantageous way. While these latter programs are principally oriented toward fundamental submillimeter physics and ground-based atmospheric, the NASA fittingly concentrates on pioneering developments directed toward technological support of space scientific projects and spaceflight operational applications.

Historically, because the revival of submillimeter techniques coincided with the inception of the NASA Electronics Research Center in 1963, the new Center's Optics Laboratory almost incidentally became NASA's principal project monitor for the programs specifically directed toward submillimeter sciences and has since grown into a focal point of national importance for submillimeter technological research and development. An additional number of supplementary projects is carried out in the Microwave and Component Technology Laboratories of the Center.

The ERC program now covers the entire range of submillimeter component technology from detectors and detector cooling, filters, lasers with their ancillary devices, and advanced interferometer wavelength separation instruments, to the applications of such devices in submillimeter spectroscopic studies of materials and gases, in astronomy and in the atmospheric sciences.

One of the principal projects underway at ERC is the submillimeter telescope mentioned earlier in this report. A photograph of the complete instrument is shown in Figure 13. A rooftop observatory (Figure 14) has been provided where auxiliary submillimeter instrumentation will be evaluated and developed for future balloonborne and, eventually spaceborne, use in these studies. It is expected that the telescope which is to have a Coudé focus configuration will make use of the experimental components, auxiliary equipments and techniques that are now being developed under other parts of the ERC program and will this way be used as a technological test facility. No decision has yet been reached on details of the final Coudé instrumentation, but the installation of a narrow-band wire mesh Fabry-Perot interferometer, which has been developed at ERC, and a gallium-doped

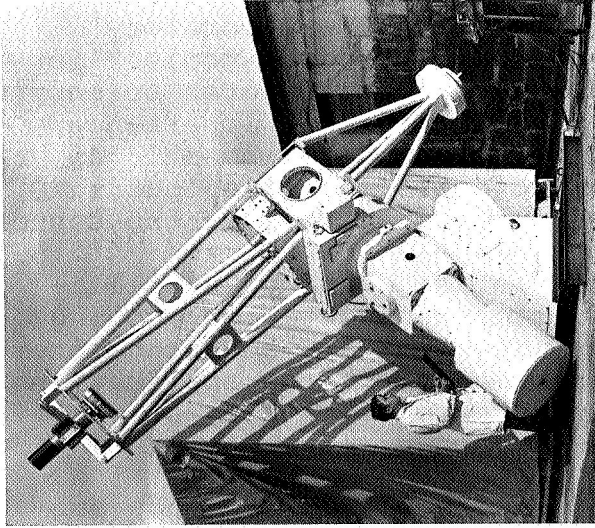


Figure 13.- Far  
infrared telescope  
for NASA/ERC

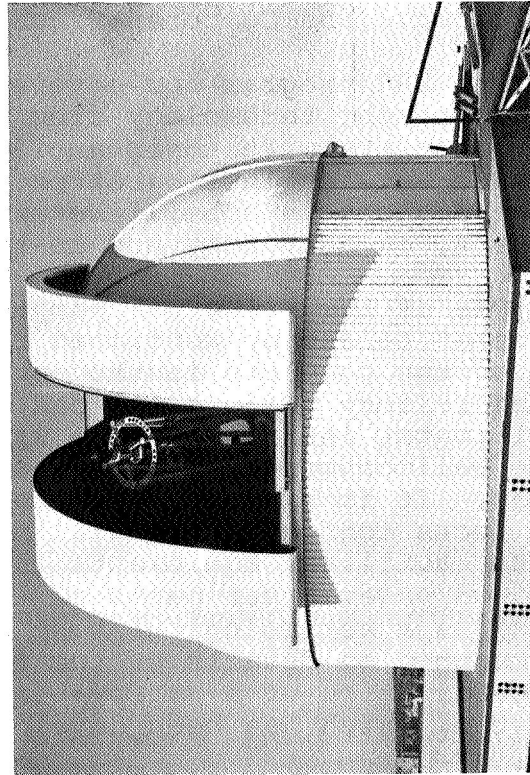


Figure 14.- ERC rooftop observatory for  
infrared astronomy technology program

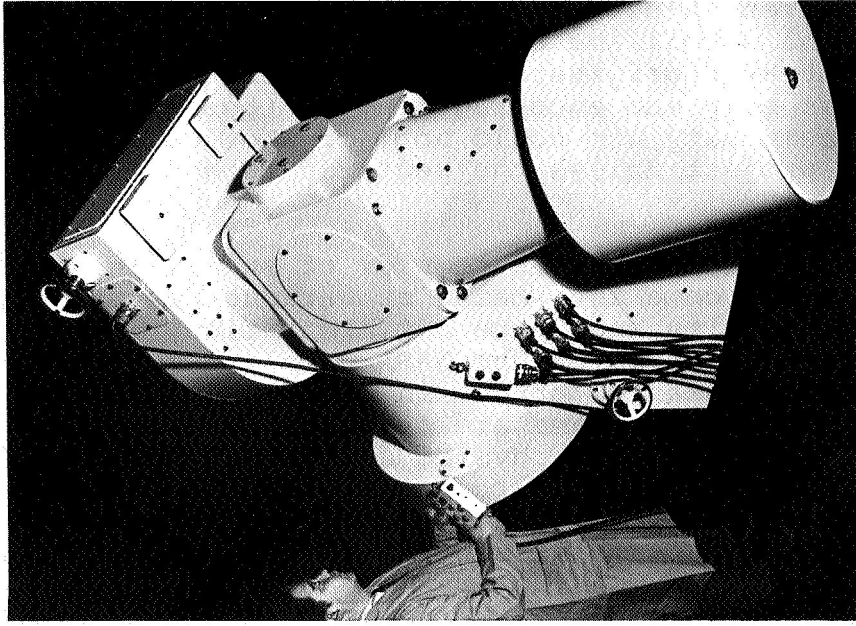


Figure 15.- Mount for ERC  
infrared telescope

germanium bolometer cooled by a closed-cycle liquid helium cooler is contemplated for the first phase of the program.

The initial design calls for a 75-cm diameter aperture, but the mount (Figure 15), which is German equatorial, will be constructed to accommodate apertures of 100 or 180 cm diameter as well, and will also have provision for solar scanning. It is planned to invite the astronomical and technological community at large to participate in both the development and the spaceborne, observational phase of this program. The balloonborne part of the program is planned to be carried out in cooperation with the University of Denver. Initial observations will concentrate on obtaining high-resolution spectra radiometer data of the Sun through one of the atmospheric windows. Subsequently, attempts will be made to detect the Crab Nebula and galactic center which are expected to be the strongest of the non-solar system sources.

The first part of the experimental program will concern itself with the determination of the kind of observations that can be carried out from the ground considering both elevated and sea level stations, and will therefore of necessity involve atmospheric studies with the Sun as a primary source of radiation. The results of these studies will determine the requirements for, and the further course of, technological development for future experiments.

By no means does the ERC submillimeter program concentrate entirely on astronomical applications, however. Submillimeter lasers, both for laboratory use and other applications, have already been put in operation and their phenomenology is being studied; techniques for the control of laser action and frequency control are being investigated. The experiences gained in an Optics Laboratory space qualification program for other lasers are evaluated for applicability to submillimeter lasers as well. The same is true of current thin-mirror technology projects which aim at the control of mirror figure for large-aperture telescopes by means of push-pull actuators. A new laboratory with extensive instrumentation for the evaluation of submillimeter as well as other detectors has been established in cooperation with the Corona, California, Naval Ordnance Laboratory. Molecular structural research is being carried out on optical materials needed in space applications and on the properties of gases abundant in the terrestrial and planetary atmospheres, together with studies on the emission of laser gases, and on the fine structure, line widths, Doppler shifts (ref. 107) and so on in the spectra of  $N_2O$ , HCN, and  $H_2O$ . The latter studies will lead to the absolute measurements of laser frequencies within a few parts in  $10^7$ .

One of the applications of general scientific interest pursued in the Microwave Laboratory in cooperation with the National Bureau of Standards is the use of an ultrastable sub-millimeter power source in the determination of the velocity of light. Taking advantage of the possibility of measuring the frequency and the wavelength independently by means of harmonic mixing, an improvement in the accuracy of at least one order of magnitude is expected from this work. The ERC Component Technology Laboratory, in particular, specializes in research on the optical and lasing behavior of bulk semiconductors in the sub-millimeter and near millimeter range.

Outside ERC, the NASA Goddard Space Flight Center, through its Institute for Space Studies, has an active pioneering research-directed program in infrared astronomy, of which a substantial portion concerns itself with submillimeter observations from balloons. As mentioned earlier, the current, initial objective of the program is the search and mapping of diffuse emissions from interstellar grains by means of a low angular resolution germanium bolometer radiometer. The instrumentation for this program is modified between flights. Thus far three have been completed.

In the light of the encouragement by authoritative consulting groups, such as the President's Science Advisory Committee and by the scientific community at large, it can well be expected that the submillimeter astronomical programs, and along with them all other related efforts, will grow both in scope and physical extent and that also other disciplines will make increasing use of this new and exciting capability as the potentials of the sub-millimeter region are more and more recognized.

#### FUTURE SUBMILLIMETER TECHNOLOGY RESEARCH NEEDS

A number of problem areas have been indicated that need to be covered if the inherent capabilities of submillimeter waves are indeed to be used to fullest advantage. While some of the possible submillimeter applications, notably ground-based ones, can already be implemented and carried to predictable success, there are others that still await the development of a specific technique or device, or possibly a rather straightforward improvement of existing hardware.

Undoubtedly, the most critical, pacesetting research required for any submillimeter wave application in space concerns the problem of cooling. While promising starts have been made, the importance of this requirement has only recently been fully

recognized, and a determined effort is needed here to move this area from fundamental laboratory research into the sphere of reliable field operation. Also, as long as only observation and detection-type activities are carried out, scientists can for an initial period get by with restricted cooling of the detector alone. However, more extensive cooling needs will doubtlessly arise when precise radiometric research is to be done and cooling systems for optical surfaces, enclosures, and shutters will have to be developed. For some special cases, old concepts, such as the tubeless telescope, might again have to be revived along with renewed research on topics such as the effectiveness of new baffling and shading arrangements. Provisions of the latter category and advanced passive cooling techniques will be particularly important for moon-based missions or long-duration, deep-space flights.

The other most pressing need for measurement-type research is still a reliable submillimeter radiation standard operating at well defined and reproducible power levels, firmly correlated with other calibration sources in other parts of the spectrum, and possibly adaptable for use in space. No useful standard of this type is yet in existence even for laboratory application and no truly accurate absolute measurements will be possible until such a source is established.

The difficulties involved in making a submillimeter standard are manifold and range from the generally insufficient intensity of the basic source -- even a carbon blackbody would yield radiances only in the order of  $10^{-9}$  watt  $\text{cm}^{-2}$  steradian $^{-1}$  micron $^{-1}$  -- and the reliability of measurements of high temperatures, to the exact separation of the required bandwidth and measurements of effective bandwidth; the determination of the radiative properties of the materials involved, and the thermal and optical control of the environment, as well as to the seemingly simple and yet complex definition and maintenance of systems geometry.

Likewise necessary is a well defined, reliable, low-noise detector and the associated operating assembly, which is equally difficult to obtain because of the current ignorance on the energy conversion processes in the detector material used and even on seemingly trivial matters such as the submillimeter absorptance of the prime absorber or on how to mount and effectively cool a detector and its housing. It is safe to state that many current claims on measurement accuracies, detectivities, and power levels achieved will topple once a reliable standard source-detector combination is available. Needed in the same line is the development of a highest-precision receiving, transmitting, and imaging system for submillimeter waves. Because, at the wavelength in question, detectors and sources can be matched in both size and shape with the diffraction figure of the optics involved,

this system could achieve optimum resolution and best possible radiometric efficiency in passive as well as active applications. Using fabrication and quality tests customary for a visible-light system, the effects of surface imperfections and figure deviations could be held in the order of 1/1000 or less of the operating wavelengths, and because also full-surface mirrors would be used -- thus avoiding uncontrolled side lobes -- the image quality obtained by such a system could be expected to be in every way optimal at a minimum system size. A system of this kind could serve as a high precision collimator and research tool for sensitive tests and simulations and would, at the same time, constitute a standard for submillimeter image quality.

Much important research can be done with limited accuracy, however, especially when the objective is observation and detection rather than precise radiometric measurement. Thus, high-sensitivity heterodyne detection techniques, which show promise in the adjacent spectral bands, will also be worthwhile studying in the submillimeter region, and image forming devices or techniques -- involving, maybe, detector arrays and mosaics and scanning methods -- will become necessary.

It still seems worthwhile to urge scientists and agencies to actively look for new, effective submillimeter image conversion principles. To raise the efficiency of receiver systems, single-mode, light-pipe techniques, and light-pipe geometries and methods to fabricate them must be developed. Supersize optics, probably foldable or self-forming, surface-controlled and configured for deployment in space, will be needed both to accommodate the low-energy levels of the objects studied and to make high-resolution scanning possible even at submillimeter wavelengths. Likewise, new materials must be examined for "color"-corrected refractive or quasi refractive, for example, Fresnel-type, optics and radiation processing devices, such as polarizers, rotators, and miniaturized submillimeter interferometers.

Requirements for so-called active operations, that is, operations using their own basic radiation source, may be even still more urgent than those for passive ones. Not only are many more wavelengths to be made accessible for a host of applications, notably to satisfy the needs for more communication channels, but the energies associated with them must be sufficient to penetrate perturbations in the path of light. Modulators and easily controllable phase shifters are so far virtually nonexistent key components for communication systems, and no submillimeter communication will be possible without a considerable effort to make them available. Similarly, new efficient tuning techniques, probably using other than Zeeman or Stark effects which require excessive power levels, are needed, especially for spectral studies of such perturbations and to provide a possibility

to match frequencies accurately with the spectral windows of both terrestrial and planetary atmospheres.

Of course, the listing of necessary techniques, components, or systems of the kind discussed in this report cannot pretend to be complete; indeed it can reflect only the most urgent and immediate needs. Moreover, it is useful to remember that any new technique or component developed not only must be capable of functioning, but at the same time it must be what is now called "space-qualified." This is a term that comprises a process encompassing, for example, hardening against meteorite impact and radiation; lifetime and reliability enhancement; conditioning against the detrimental influences of space temperature and temperature differentials, pressure and gravity; adaptation to allowable space, weight, and power requirements, and many others. Even the most limited list of new development requirements therefore reaches into manpower and funding resources of many years ahead, and a most careful decision will be necessary to establish where priorities should be placed and where tradeoffs should be accepted.

#### CONCLUSION

This report has undertaken to review the status of present submillimeter science outside the area of molecular spectroscopy and to communicate at the same time an impression of its rather dramatic development during the current decade. While 10 years ago the submillimeter range was primarily known as "the gap," scientists now appear to move with a considerable degree of freedom through the region. Most of this development can be directly traced to the impact of the space program. The new scientific discipline of submillimeter astronomy is emerging from this combination and other applications are constantly opening up for submillimeter waves. NASA has appropriately taken the lead in developing the new technology required for the utilization of the new capabilities and a new focal point for the submillimeter sciences is forming at the NASA Electronics Research Center. While the basic submillimeter technology for passive detection and observation tasks is available, "active" operations lag behind, and measurement-type experiments must still wait for the development of reliable absolute standards.

Perfectionists' contempt notwithstanding, physicists obviously can now rightfully claim that the barriers still surrounding the submillimeter "gap" are indeed crumbling. Closing this gap will accomplish vastly more than just satisfying a desire to do a scientific good deed or to remove a blemish that in some intellectual esthetes has caused feelings of discomfort and embarrassment. Quite distinctly the achievements of the last decade



prove that through diligent use of submillimeter waves a vast number of problems, both in the universe and close to Earth, can be brought nearer to their solution and that this still wide open and rewarding field deserves indeed the encouragement and determined support urged by high-level scientific authorities.

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National Aeronautics and Space Administration  
Electronics Research Center  
Cambridge, Massachusetts, April 1968  
125-22-02-33

APPENDIX A  
POSSIBLE SPACEBORNE SUBMILLIMETER EXPERIMENTS

Cosmology

1. Radiation from interstellar grains (ref. A-1)
2. Submillimeter celestial mapping (ref. A-2, Part 2, page 107)
3. Synchrotron sources (Quasars, Crab Nebula, etc.) (ref. A-3)
4. Mapping of low temperature celestial bodies, stars and star clusters (protostars, dense clouds, etc.) (ref. A-3)
5. Molecular hydrogen and Ne++ line radiation (ref. A-4)
6. Cosmic background radiation (ref. A-3)
7. Celestial natural laser action (ref. A-3)
8. Continual monitoring of time-varying sources (Quasars, HII regions, late stellar evolutionary stages (ref. A-3; H. Weaver, in ref. A-5, page 16)
9. Thermal emission from galactic HII regions (galactic center, planetary nebula) (refs. A-6,7)

Solar Physics

1. Measure complete solar spectrum and total solar flux
2. Determine point of neutral solar limb (neither darkening nor brightening)\*
3. Propagation of solar events, e.g., proton acceleration through solar atmosphere (J.W. Warwick, ref. A-5, page 35)
4. Structure of low chromosphere (R.J. Coates, ref. A-5, page 43) and compare with structure found in photosphere using other parts of spectrum (J.W. Warwick, ref. A-5, page 27)
5. Use of sun as reference source for radiative output\*\*
6. Determine gradient and minimum of solar brightness temperature (ref. A-2, Part 2, page 34)
7. Revision of solar models (ref. A-8)

Planetary Sciences

1. Dielectric constant of lunar or planetary surface (ref. A-2, page 107; ref. A-9; ref. A-10)
2. Upper atmosphere transmission (water vapor, trace constituents)
3. High resolution spectroscopy of Jupiter and Venus

Atmospheric Optics

1. High resolution measurement of atmospheric windows for sub-millimeter radiation (ref. A-11)

Spaceflight Operations

1. Space-to-space pulse communication
2. Rough pointing

\*Private communication, L. Goldberg, Harvard College Observatory  
Cambridge, Mass.

\*\*Private communication, A. Unsold, Univ. of Kiel, Germany

APPENDIX B  
DEFINITION OF "OPTICS"

1. "...The study of the phenomena associated with the generation, transmission and detection of electromagnetic radiation in the spectral range extending from the long-wave edge of the X-ray region to the short-wave edge of the radio region. This range, often called the optical region of the electromagnetic spectrum, extends in wavelength from about 10 angstroms to about 1 mm." (ref. B-1)
2. "...The range of waves from a few millimeters to  $2.5 \times 10^{-2}$  mm in length is known as the far infrared region, that from  $2.5 \times 10^{-2}$  to  $7.5 \times 10^{-4}$  mm is known as the near infrared. Waves that can be seen by the eye range in length from  $7.5 \times 10^{-4}$  mm in the red to  $4 \times 10^{-4}$  mm in the violet; this range is called the visible region. Waves slightly too short to see,  $4 \times 10^{-4}$  to  $3 \times 10^{-4}$  mm, lie in the near ultraviolet; then come the far ultraviolet; and the extreme ultraviolet regions, which extend from  $3 \times 10^{-4}$  to  $2 \times 10^{-4}$  mm and from there to  $2 \times 10^{-6}$  mm, respectively. Since air is opaque to these shorter waves, they are studied in vacuum, and the range from  $2 \times 10^{-4}$  to  $2 \times 10^{-6}$  mm is also known as the vacuum ultraviolet." (ref. B-2)
3. "...It is the meaning of optics to include radiant energy propagated by waves that are either too long or too short to be perceived by our eyes, but which can be studied by essentially the same methods as are used for the visible region." (ref. B-3)

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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